

UV-curable liquid-core fiber lenses with controllable focal length

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Abstract: Lensed fiber optics is of great importance to many applications such as optical sensing, optical coupling, laser trapping etc. In this paper we have demonstrated a unique method to fabricate liquid-core lensed fibers by filling UV curable adhesive into hollow fibers, and to control the focal length and spot size by pumping liquid into or out of the fiber end. In experiment, tuning of focal length from 2.414 to 0.810 mm has been obtained, and solidification of the adhesive core has also been carried out successfully. Further simulation suggests that the focused spot size can be reduced to <10 micron by adjusting the refractive index and fiber geometry. Such technique has the potential to manufacture custom-made solid lensed fibers and liquid-core solid-tip lensed fibers in volume at low cost. The same technique may be used for input and output coupling of optofluidic waveguides with external optical components like optical fibers and lasers.

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1. Introduction

Liquid-core waveguide has the merit of sensitivity enhancement and is of great interest to many sensing applications such as fluorescence and Raman measurements, long-path-length UV–visible absorption/transmission, and IR spectrometry [1]. It is also essential for supercontinuum light generation, nonlinear optics, spectroscopy and biomedical sensing [2, 3]. In addition, it is an economical choice for transmitting light in the deep UV region down to ~200 nm with a large core diameter and a wide acceptance angle as compared to the fused silica for pollution measurements [4].

On the other hand, adding a liquid lens at the end of a liquid-core waveguide presents to be an effective way to control the spot size for input/output coupling. Lenses made of liquid have the unique ability to quickly change the shape and focal length and can act as focusing lenses for miniature cameras and optimal optical coupling [5]. Variable liquid focus lens can be achieved by pressure-induced deformation of a liquid interface [6], or by the laminar flow of three streams of liquid [7]. Traditional approaches like electrowetting require high voltage. It will be less complicated if the shape and size of liquid lens are controlled by mechanically pumping the liquid into or out of the tip region of waveguide. In this way, the focusing power of liquid lens can be adjusted without changing the lens aperture [8]. Such idea can be further developed to fabricate solid-state lensed fibers, which have great commercial market for the applications in diode laser pigtailed, semiconductor laser coupling systems, biomedical sensing, mode-matching waveguide devices and laser trapping [9–13]. The design of the lensed fibers depends greatly upon the applications. Some may require collimated output beams while some others require tightly focused beams. The development of optimized solid-state lensed fibers usually involves complicated theoretical calculation and intricate fabrication such as mechanical polishing, melting and thermal molding [14, 15]. Therefore the whole development process is time-consuming, costly and not flexible.

In this paper, a low-cost method is proposed for the fabrication of optimized lensed optical fibers. This method starts with filling the hollow fibers with UV curable adhesives to form the core. Then the shape (commonly spherical) of the liquid lens at the fiber tip can be adjusted continuously by controlling the pumped volume of liquid. Aspherical lens shape is also possible by applying high-intensity electric field [16]. Optimization of the lens shape is achievable by monitoring the coupled optical power or beam diameter. After that, the lensed fiber could be solidified by exposure to the UV light. This method would enable the manufacture of high-end customized lensed fibers in volume and at low cost.

2. Experimental setup and results

Here design, fabrication and characterization of the lensed liquid-core fibers with a silicate cladding will be elucidated, and solidification of the lensed fiber end will be presented as well. The schematic diagrams are shown in Fig. 1. In conceptual design, a hollow fiber is first tapered and then cut into a flat end. After that, it is filled with UV curable adhesive using a syringe. At the fiber tip, a liquid lens is formed by the surface tension, and its shape and size can be controlled by adjusting the position of syringe piston, or equivalently, the volume of liquid at the fiber tip (see Fig. 1(a)).

In fabrication, the hollow silica fiber had an initial inner diameter of 2.25 mm and an outer diameter of 3.65 mm. It was tapered to 0.167 mm and 0.854 mm, respectively, by a fiber drawing tower developed in our research laboratory. To lead in the light from a pigtailed red laser (wavelength 655 nm), an optical fiber (outer diameter 0.125 mm) was threaded into the tapered fiber. Then, the UV curable adhesive (Norland NOA61) was manually pumped in using a syringe. NOA61 has a refractive index of 1.527, slightly larger than that of silicate glass (refractive index ~1.525). The NOA61 core and the silica cladding formed effectively a step-index liquid-core solid-cladding waveguide. Thanks to the slow tapering, the red laser beam from the optical fiber was concentrated and redistributed automatically in the tapered

liquid core (see Fig. 1(a)) and did not need a careful alignment between the optical fiber and the inner side of the tapered hollow fiber. However, the optical loss through the tapered region is depending on incident angle of the light to the liquid fiber core, tapering angle and numerical aperture of the liquid core fiber [17]. This brings in much convenience for fabrication, experiments and applications.

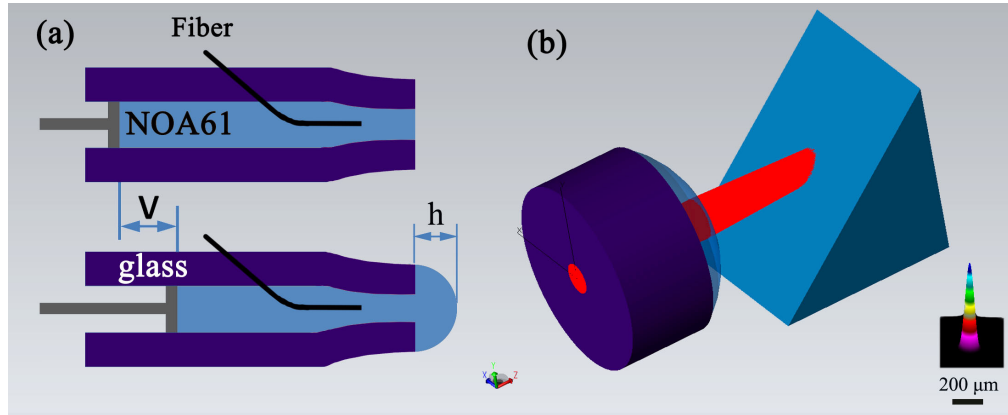


Fig. 1. (a) Working principle of the lensed liquid-core waveguide. (b) Simplified optical model of silicate glass taper with NOA61 lens in TracePro, the inset shows the irradiance of the 45° screen with 655 nm red laser simulated by TracePro.

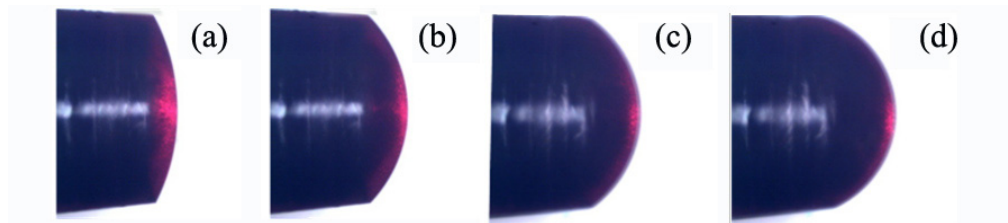


Fig. 2. The liquid NOA61 volume is increasing with radius of curvature of the liquid lens reducing from (a) to (d) while keeping the lens aperture the same.

The aperture of the liquid lens is determined by the cladding diameter of the tip, however, the radius of curvature and focal length can be modified by pumping in or out the liquid as demonstrated in Fig. 2. The liquid lens is a small plano-convex lens as the surface tension dominates over other forces, e.g. gravity. Theoretically, the effective focal length f of liquid lens can be expressed as

$$f = \frac{1}{n_{liquid} - 1} \cdot \left(\frac{h}{3} + \frac{V}{\pi \cdot h^2} \right), \quad (1)$$

where h is the thickness of liquid lens, V is the volume and n_{liquid} is the refractive index. Using the parameters given above, the relationship between the focal length and the volume is plotted in Fig. 3(a). It is seen that the focal length is reduced from 2.414 to 0.810 mm when the liquid lens volume is increased from 0.021 to 0.163 μL. The lens aperture is maintained at ~0.854 mm. In experiment, the spot size and focal length were determined by projecting the laser beam onto a 45° screen placed under a microscope (see Fig. 1(b)). The image was captured by a CCD camera mounted on the microscope and then analyzed by a Matlab software tool written by the authors.

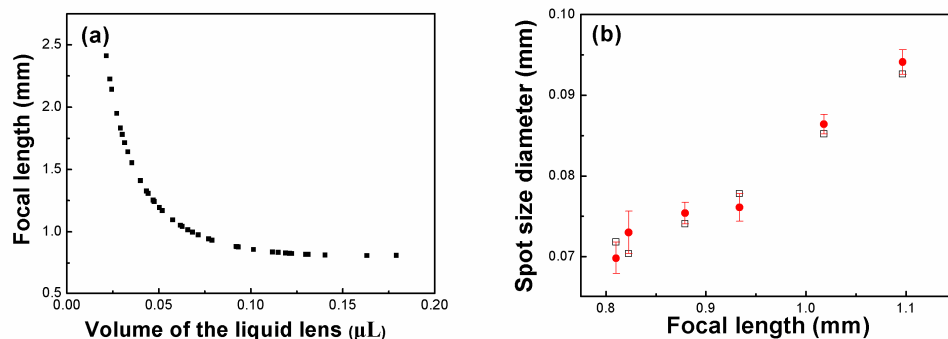


Fig. 3. (a): Relationship between the focal length and the volume of NOA61 lenses (refractive index 1.527, fixed lens aperture ~ 0.854 mm). (b) Change of the laser FWHM spot diameter with the focal lengths. Hollow square: calculated value; Red circle with error bar: measured value.

The commercial optical engineering software, TracePro, is used to simulate the red laser ray tracing in the study. The program can perform stray light analysis, illumination analysis, and optical systems analysis. It uses Monte Carlo ray tracing method to compute optical flux as it propagates through the lensed waveguide [18]. Then rays can be traced through the system to find energy distributions on 45° screen. For ray tracing simulation, the model of the silicate glass waveguide with NOA61 core and lens is established. The optical properties of every element are assigned in reference to the experimental section reported. The geometry of the glass tube is filled with NOA61 with core diameter of 0.167 mm, cladding diameter of 0.854 mm. The distance between the end of glass tube and the 45° screen, L , which is kept constant to be 0.8 mm. The hollow square of Fig. 3(b) shows the calculated laser FWHM spot size diameter with respect to various focal lengths of the NOA61 liquid lens. Figure 3(b) shows the experimental measurement matches very well with the stimulated FWHM spot size. Figure 1(b) illustrates optical modeling of red laser guide through the NOA61 silicate glass lensed waveguide and the inset describes 3D beam profile on the 45° screen, when the focal length of the liquid lens is 1.02 mm.

Solidification of NOA61-core lensed fibers

The NOA61 lensed liquid-core fiber can be solidified by exposing to UV light after output spot size is tuned into the desirable value. In this way, lensed fiber with optimized focal length can be fabricated for various applications for the optical industry, e.g. to couple diode laser light into the optical fiber. To demonstrate this concept, a solidified lensed NOA61 fiber has been fabricated under exposure of UV lamp and Fig. 4 shows the NOA61 lensed fiber (a) before and (b) after solidification. Figure 4 indicates the size of the lens almost has no significant change after solidification and smooth lens surface can still be maintained. However, according to the information from supplier of the NOA61, it should have very small linear shrinkage of 1.5% and the refractive index of the NOA61 will increase from 1.527 to 1.560 after solidification. Since the refractive index of fiber core increases, the NA of the fiber reduces and more focused spots will be obtained after the solidification. The lensed fiber can be partly exposed to UV light to form a solid tip lens with liquid waveguide structure.

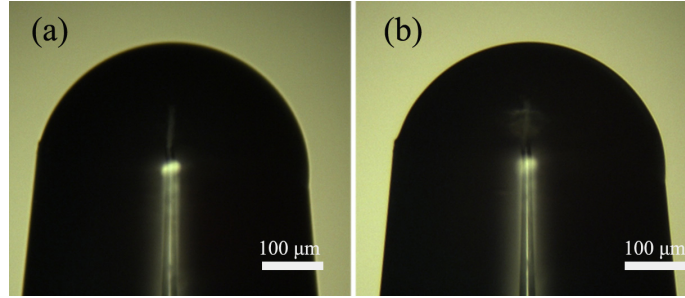


Fig. 4. (a) lensed liquid lens with liquid NOA61 adhesive ($f = 0.412$ mm) (b) lensed liquid lens with solid NOA61 adhesive after UV solidification ($f = 0.3875$ mm).

Further spot size reduction of lensed liquid-core fiber

The focused spot size of the lensed liquid fiber depends on the fiber dimension and refractive indices. The following stimulation by TracePro indicates that the focuable spot size from the lensed fiber can be changed by adjusting the refractive index ratio and the diameter of the cladding. Assuming that the hollow liquid fiber has standard single mode optical fiber geometry with core and cladding diameter of $8\ \mu\text{m}$ and $125\ \mu\text{m}$ respectively. The liquid lens shape is semi-spherical. The simulation results in Fig. 5(a) shows the spot size is reducing as the refractive index of the core and cladding ratio is getting close to unity, which implies that the spot size is reducing when the refractive index of the core and cladding is getting close to each other.

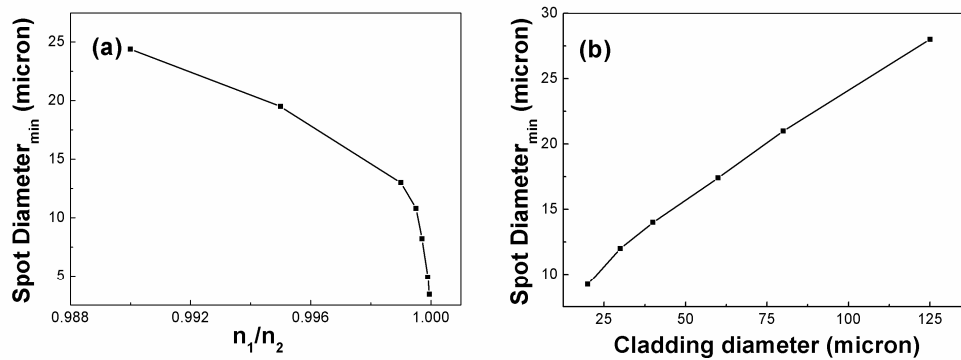


Fig. 5. (a) Simulated spot size diameter at the focus against refractive index of core, n_1 and refractive index of cladding, n_2 ratio. Hollow core diameter = $8\ \mu\text{m}$, Cladding diameter = $125\ \mu\text{m}$, lens shape is hemisphere. (b) Simulated spot size diameter at the focus against cladding diameter of the hollow fiber. Hollow core diameter = $8\ \mu\text{m}$, lens is hemisphere, setting $n_1/n_2 = 0.985$ as for the NOA61-core lensed fiber.



Fig. 6. The diameter of the lens is very close to the diameter of the fiber core with the droplet radius of 110.9 μm .

Assuming that the refractive index of the core and cladding is the same as the demonstrated NOA61-core lensed fiber, Fig. 5(b) indicates the focused spot size can be further changed from 28 μm to 9.2 μm for varying the cladding diameter from 125 μm to 20 μm . The lens diameter can be practically set smaller than the fiber cladding at the right pressure as shown in Fig. 6. A circle (physical boundary) can also be inscribed over the surface of the fiber tip to make the liquid lens with smaller radius. Further focusable spot size can be further minimized by drawing into a smaller fiber. The fiber, which has a hollow core and cladding diameter of 8 μm and 20 μm with the ratio of 0.4, can be drawn into smaller fiber with the same core and cladding diameter ratio. With the fiber with a core and cladding diameter of 4 μm and 10 μm , and the refractive index same as the demonstrated NOA61-core lensed fiber, the stimulated focused spot size is around 1.5 μm , which is close to the calculated spot size limit, $S = 1.554 \mu\text{m}$ according to Eq. (2).

$$S = \frac{\lambda}{d(n_{\text{liquid}} - 1)} \cdot \left(\frac{h}{3} + \frac{V}{\pi \cdot h^2} \right), \quad (2)$$

3. Conclusions

Liquid waveguide technique has been explored to fabricate lensed fibers with customized performance. Lensed fibers with NOA61 UV curable adhesive as the core (diameter 167 μm) and a tapered silicate glass hollow fiber as the cladding (diameter 854 μm) have been fabricated successfully. Controllable focal length $f = 2.414 - 0.810 \text{ mm}$ in response to a change of the liquid lens volume from 0.021 to 0.163 μL has been demonstrated successfully. The solidification of the lensed fiber tip has also been successfully demonstrated by the exposure of UV light. The stimulation shows the focused spot size can be further reduced to <10 micron by adjusting the refractive index, fiber geometry. Therefore, the lensed fibers can be further miniaturized by using fiber tubes with smaller diameter and the lens size and shape can be controlled precisely using pressure-driven mechanisms such as piezo electric stack actuators and external pumps. Elastic rubber or membrane can be added to enclose the liquid lens to avoid evaporation of the liquid.

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